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Review

Individual collision risk assessment in ship navigation: A systematic literature review

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ABSTRACT

The increasing attention to the improvement of navigational safety and autonomous navigation has led to the emergence of various tools and methods for collision risk assessment in ship navigation. An extensive systematic literature review has been carried out in this paper. It focuses on the parameters and methods of individual collision risk assessment providing input for navigational safety and autonomous navigation. We thoroughly assessed and analysed a number of papers on this topic, according to two dimensions: a model-based analysis, and a parametric clarification. Through this review, we seek to provide a greater understanding of the use and integration of parameters and methods in individual navigational collision risk assessments. Additionally, the information obtained through systematic literature review not only makes it possible to identify current circumstances, trends, and deficiencies, but also helps to focus future efforts. The results of the systematic literature review also indicate a literature gap regarding navigational collision risk assessment.

1. Introduction

In recent years, ship manoeuvrings in congested waters have become more complex with the emergence of specialized vessels and increasingly larger ships. Therefore, collision avoidance in congested waters has turned into one of the most important concerns in providing navigational safety. The International Maritime Organization (IMO)'s standardization efforts and the International Regulations for Preventing Collisions at Sea (COLREG) have introduced useful, practical and reliable methods to ensure navigational safety. Additionally, manoeuvring decision support systems constitute an essential facilitating device to enhance collision avoidance capability and increase navigation safety. As a basic and significant concept in ship navigation, collision risk assessment is a fundamental pillar of these supporting systems. Hence, an effective and systematic model for continually assessing collision risk by monitoring parameter states is necessary.

It is possible to find numerous examples of collision risk assessment in the literature. Each method has its advantages and disadvantages. However, due to the large number of feature parameters, the inherently complex marine environment, uncertainty and a lack of information, there is no common ground to define collision risk. Furthermore, no references have been made to the foundation of risk analysis in the maritime application area (Goerlandt and Montewka, 2015). The selection of appropriate and consistent collision risk assessment methods generally depends on each unique situation. Collision probability models evaluating potential collision occurrence are rooted in the research carried out by Macduff (1974) and Fujii et al. (1974). These studies assumed that the number of vessels is randomly distributed on the waterway considered. That is, they employed the frequency of vessels' navigation on the specific water area. This approach emphasizes potential accident candidates, allowing the evaluation of any given waterway, such as the Gulf of Finland (Montewka et al., 2010), the Yangtze River (Zhang et al., 2013) and the Strait of Istanbul (Ulusçu et al., 2009). Unlike collision probability, individual collision risk represents the degree of collision only in respect to specific parameters. There exist also other characteristics of individual collision risk. For instance, individual collision risk models are independent from the frequency data of any waterway. They allow for an evaluation of any type of waterway (open sea, restricted waters, and so on) in a macroscopic way. Furthermore, individual collision risk models serve as foundation for collision avoidance models and can feed them with a Navigational Collision Risk (NCR) degree. Therefore, in the remainder of this paper, NCR refers to Individual Navigational Collision Risk. A basic graphical representation of the relation of the NCR assessment, collision avoidance and maritime transportation risk analysis assumed in this study is presented in Fig. 1.

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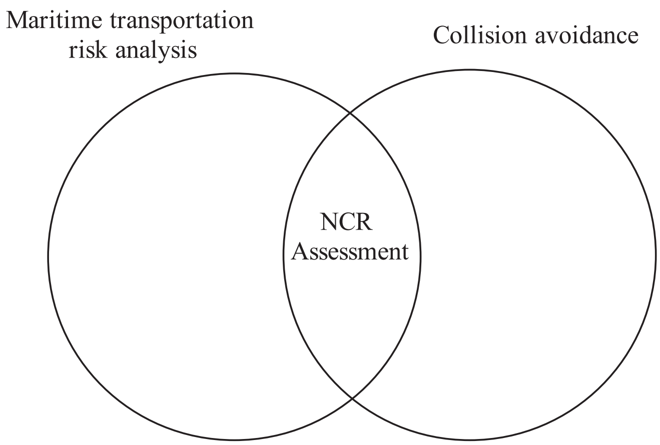


Fig. 1. A basic relation of NCR assessment, collision avoidance and maritime transportation risk analysis.

The scope of this study is determined by the classification of risk definitions of Goerlandt and Montewka (2015). This allows us to reveal not only the risk definitions of NCR assessment studies, but also the parameters utilized in the risk approach.

Some authors (Szlapczynski and Szlapczynska, 2017) analysed ship domain-based parameters in ship collision in order to overcome the limitation of navigation-specific parameters. Xu and Wang (2014) reviewed ship collision risk evaluation studies according to their own parameters. However, the aim of the present paper is to investigate individual collision risk models, the parameters featured in these models, and the application of methods and tools in the literature. This analysis aims to provide broader insight and knowledge of perceived trends and existing difficulties. Furthermore, it can provide greater focus to the future efforts, by training the lens on collision risk models in a macroscopic way. As additional support to this analysis, we present the feature parameters that feed the models and information flow.

This paper is organized as follows: Section 1 introduces the research methodology and the results of the systematic literature review. In Section 2, we conduct a classification of NCR assessment models. Section 3 discusses the applications of NCR assessments in collision avoidance systems. In Section 4, we evaluate the parameter analysis results. Section 5 presents a discussion, followed by the conclusion.

2. Research context

We reviewed NCR studies based on the characteristics defined in Table 1. These characteristics were firstly presented by Goerlandt and Montewka (2015) in order to figure out the research context of the literature review in risk analysis.

The classification of the characteristic “adopted approach to risk analysis science” shown in Table 1 is determined in reference to studies by Bradbury (1989), Rosa (1998) and Goerlandt and Montewka (2015). According to Bradbury (1989) and Rosa (1998), realist, constructivist and proceduralist approaches are accepted as three common views on risk analysis. However, Goerlandt and Montewka (2015) modified these approaches for maritime transportation and presented eight scientific risk analysis approaches: (I) strong realist, (II) moderate realist, (III) moderate realist with uncertainty quantification, (IV) scientific proceduralist, (V) precautionary proceduralist, (VI) moderate constructivist with uncertainty evaluation, (VII) moderate constructivist, and (VIII) strong constructivist. The authors clearly explained the characteristics of each risk analysis approach (Goerlandt and Montewka, 2015, p. 118). An overview of the adopted scientific approaches to risk analysis shows that three approaches are the most common in the application of maritime transportation risk analysis: strong realist, moderate realist and moderate constructivist. Based on this insight, the studies reviewed here are classified in respect to these three approaches.

Table 2
Review protocol.

Subject	Description
Databases	Elsevier *(Scopus and Science Direct),* Web of Science
Keywords	Navigation, collision, risk, ship
Search field	title, abstract, keywords
Boolean Operators	OR, AND
Exclusion criteria	See Table 1
Publication type	Journal and Conference papers
Publication language	English
Time interval	1970–October 2018

We conducted our literature review according to the review protocol illustrated in Table 2. A search of the selected databases resulted in a list of a total of 237 studies. Then, these studies were analysed based on whether they fit into the scope of our research. Finally, 34 studies were selected to be reviewed.

The selected papers were grouped into different categories, according to year of publication, journal, and adopted scientific approach to risk analysis, as seen in Figs. 2–4, respectively. According to Fig. 2, the number of studies on NCR shows an increase starting in 2005. The years 2010, 2015 and 2016 featured the highest number of studies published. Fig. 3 represents the number of publications in respect to journals and conferences. Accordingly, approximately 46 per cent of NCR studies were published in three journals—namely, *Ocean Engineering*, *Journal of Navigation*, and *Safety Science*. As a final categorization illustrated in Fig. 4, NCR studies were classified based on the adopted approaches to risk analysis science. Although the parameters employed in the studies resemble each other and are correlated with one another, a strong realist risk analysis approach was most commonly found, with a percentage of 56.

3. Classification of individual collision risk models

NCR assessment applications in maritime transportation are lacking in clarity when it comes to foundational issues and key terminology in the scientific methods of risk analysis (Goerlandt and Montewka, 2015). The reason behind this deficiency may be found in the wide variety of data sources, approaches and unclear boundaries of safety limits in NCR. For example, NCR assessment studies are generally based on data sets obtained through expert views via surveys (Chin and Debnath, 2009; Inoue, 2000; Lopez-Santander and Lawry, 2017), results of

Table 1
Scope of research according to characteristics (Goerlandt and Montewka, 2015).

Characteristic	Measure
Analysis aims and scope	Individual navigational collision risk
Applied definition of risk	All
Applied tools to measure risk	Quantitative/qualitative indicator, fuzzy numbers, subjective/modelled probability
Weather events, or events and consequences are accounted for	Events
Applied types of evidence	Data, model and expert judgments
Consideration of contextual attributes	None
Adopted approach to risk analysis science	Strong realist, moderate realist and moderate constructivist

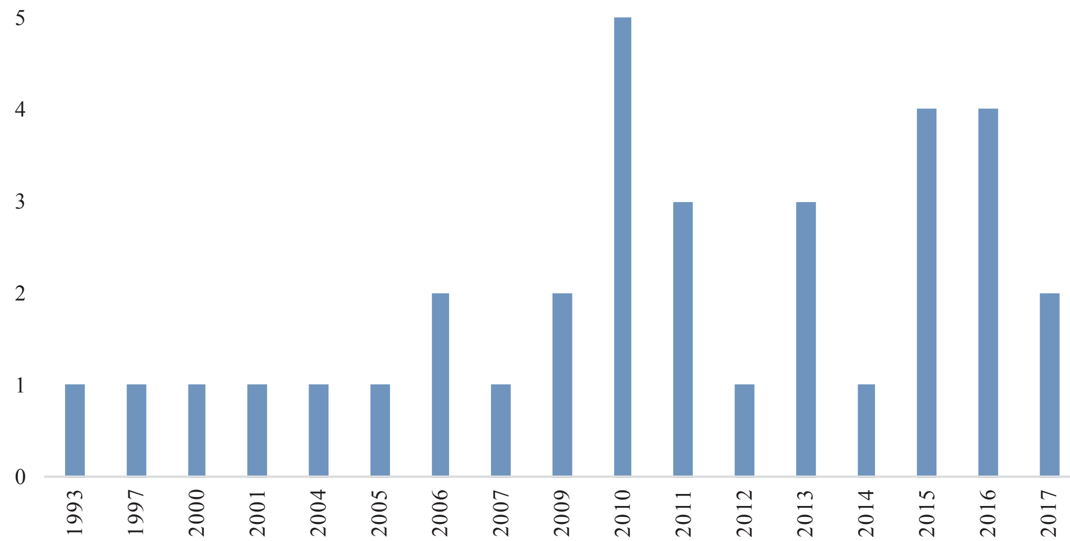


Fig. 2. Number of papers selected, organized by year of publication.

simulator experiments (Ahn et al., 2012), or data of Automatic Identification System (Debnath et al., 2011; Mou et al., 2010). Moreover, some NCR studies include mathematical functions (exponential, trigonometrical, logarithmic, and so on), fuzzy membership functions, or statistical methods. The outcomes of the functions have generally been classified according to rule-based methods or limit values provided by the perennial experience of the maritime environment. However, interpreting the limit/critical values constitutes the most controversial step of NCR assessment studies. For example, the International Regulations for Preventing Collisions at Sea (COLREGS) does not provide any standards for the safe passing distance of two encountering ships in diversified states of maritime traffic. This finding is also supported by various other authors (He et al., 2017; Zhang et al., 2015). Thus, many authors preferred to use mathematical functions to formulate the limits of the ship domain (Kijima and Furukawa, 2003; Wang, 2010), safe distance, and other critical factors to fill the gap of safety limit standards on which NCR assessment models have been built.

There also exist navigation-specific terminologies, such as "ship domain," which can reflect differently on the interpretation of risk analysis. The term "ship domain" was first introduced by Fujii and Tanaka (1971), as "a two-dimensional area surrounding a ship which a navigator must avoid—it may be considered as the area *of evasion*."

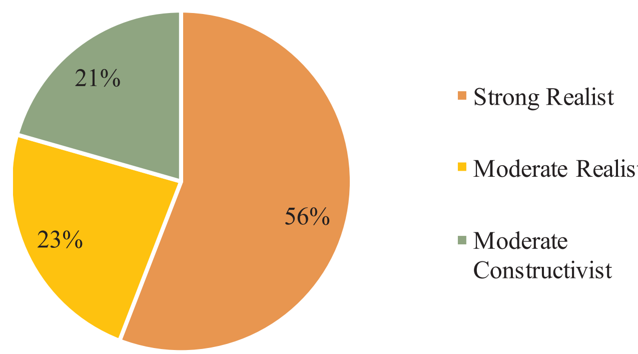


Fig. 4. Distribution of studies.

Subsequently, Goodwin (1975) defined ship domain as "the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles." However, determining a ship domain includes many unsolved problems, and as of yet no ship domain model has been widely accepted. Although a wide variety of ship domain models exists in the literature (Szlapczynski and Szlapczynska, 2017), there are several limitations, such as an

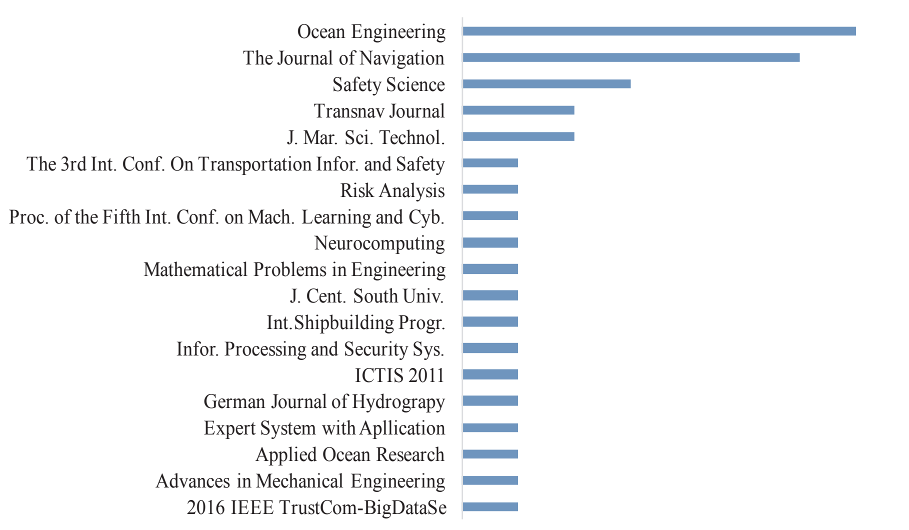


Fig. 3. Number of publications by journal.

Table 3
Aims and models of the examined NCR studies.

Author	Aim of the study	Measurement model
Kinzo Inoue, 2000	Evaluating the ship handling difficulty	Linear Regression
Chin and Debnath (2009)	Collision avoidance	Linear Regression
Lee and Rhee (2001)	Collision avoidance	Fuzzy Reasoning
Xu et al. (2010)	Maritime transportation safety	Fuzzy Comprehensive Evaluation
Bukhari et al. (2013)	Facilitating the workload of VTS operators	Fuzzy Reasoning
Zhao et al. (2016)	Collision avoidance	Evidential reasoning
Balmat et al. (2009)	Individual ship risk factor	Fuzzy Reasoning
Lopez-Santander and Lawry (2017)	Collision avoidance	Linear Regression
Zhang et al. (2017)	Detecting possible near miss collision	Fuzzy Reasoning
Wang (2010)	Reasonable ship domain model	Mathematical model
Tam and Bucknall (2013)	Path planning	Mathematical model
Ren et al. (2011)	Collision avoidance	Fuzzy Reasoning
Gang et al. (2016)	Supporting pilots with collision risk degree	Support vector machines and Fuzzy Comprehensive Evaluation
Chen et al. (2015)	Collision avoidance	Fuzzy Comprehensive Evaluation
Wen et al. (2016)	Collision avoidance	Fuzzy Comprehensive Evaluation
Chen et al. (2014)	Collision avoidance	Fuzzy Comprehensive Evaluation
Hilgert and Baldauf (1997)	Evaluate the risk of collision for pilots, officers, etc.	Rule based
Mou et al. (2010)	Real time collision risk analysis	Mathematical model
Perera and Soares (2015)	Collision risk assessment in integrated bridge system	Mathematical model
Li and Pang (2013)	Collision risk assessment	D-S Evidence Theory
Goerlandt et al. (2015)	Collision alert system	Fuzzy Rule based
Ahn et al. (2012)	Collision avoidance	Fuzzy rule based and neural network
Smierzchalski (2005)	Collision avoidance and trajectory planning	Mathematical model
Hara and Nakamura (1995)	Assessment of the safety of the shipping traffic	Linear Regression

Purposes of the examined NCR assessment studies.

Author	Aim of the study	Measurement model
Perera et al. (2011)	Decision support of ocean going vessel or autonomous ocean navigation	Fuzzy Rule based
Lisowski (2004)	Collision avoidance and officer training	Mathematical model
Kao et al. (2007)	Support VTS operations in harbour entrance	Fuzzy Rule based
Smolarek and Śniegocki, 2013	Maritime transportation safety	Linear Regression
Balmat et al. (2011)	Prevent oil pollution	Fuzzy Reasoning
Liu and Liu (2006)	Collision avoidance	Fuzzy Comprehensive Evaluation
Zhang et al. (2015)	Detecting possible near miss collisions	Mathematical model
Zhang et al. (2016)	Detecting possible near miss collisions	Mathematical model
Szlapczynski (2006)	Collision avoidance	Mathematical model
Meng et al.	Forecasting shipping accident	Mathematical model

insufficient training sample (Zhu et al., 2001), leaving out human and environmental factors (Wang et al., 2009), and complex shapes (Pietrzykowski, 2008). Because the ship domain approach and the NCR approach can be nested, in this study we consider the concept of the ship domain a navigation-specific tool of NCR. Therefore, studies calculating the collision risk index with the help of the ship domain are also examined here.

In order to clarify uncertain points of NCR terminology, we have employed the classification system proposed by Goerlandt and Montewka (2015) for scientific approaches to risk analysis. Based on their classification system, the NCR assessment models proposed in the reviewed studies were grouped under three categories: Strong Realist, Moderate Realist, and Moderate Constructivist. The motivation behind this classification is to provide insight into which risk approach the various NCR assessment models have adopted.

In this section, we scrutinized several NCR assessment models one by one and grouped them in respect to their approaches and parameters, which separately highlight the various features of the models. Table 3 presents an initial review of the aims and risk assessment models of the NCR studies.

3.1. Strong realist models

The characteristics of strong realist models are defined by Goerlandt and Montewka (2015) as follows:

i. Risk is considered to exist objectively as a physical attribute of a system, and the analysis is presented as an estimate of this underlying true risk.
ii. It exclusively relies on data collected from the system or on engineering science model.
iii. Expert judgment is not considered a source of evidence.
iv. Evidence uncertainty is not considered.
v. Stakeholders are not involved in the process of analysis.
vi. There exists a strict separation between facts and non-epistemic values.
vii. Contextual risk attributes are not considered.
viii. There exists a strong relation to established risk decision criteria.

Based on these characteristics, the specific studies proposing strong realist models for NCR assessment were ascertained. As an initial study, Hilgert and Baldauf (1997) proposed a rule-based collision risk model of ship to ship encounters for open sea waterways. This study formulated a four-level risk based on CPA (Closest Point of Approach) and proposed critical limits: hydrodynamic safe passing distance (C_H), safe passing distance (C_A), safe range (R_A), critical range (R_c), and manoeuvring range (R_M). The Safe Passing Distance (SPD) indicating the acceptable safe distance in a ship to ship encounter and its formulation are presented in Eq. (1) below:

$$C_A = f_x * L_{max} + C_g \tag{1}$$

In this equation, f_x is a factor determined by visibility and encounter situation, L_{max} is the maximum ship length, and C_g is the maximum positioning and evaluation error. C_H and R_c indicate the limit of an unacceptable DCPA and distance in a two-ship encounter, respectively. The authors assume danger of collision when the CPA and the distance between the two ships are smaller than C_H and R_c, respectively. However, the calculation of C_H was not determined because of the impracticability of measuring the real distance between two encountering ships. Therefore, the authors preferred to determine C_H from a practical point of view.

Another important study featuring a strong realist model was authored by Smierzchalski (2005) proposed a hexagon-shaped area of danger to state NCR. The author formulated six distances from the center of the ship to establish the safe navigation/manoeuvring area with the help of TCPA, DCPA, own speed, relative speed, ship length, and ship breadth parameters. Stern and port side safe distances were assumed to be no less than 0.5 miles. Also, the author suggests that the safe distance in front of the bow should be 2 to 3 miles; anything below this distance results in collision risk. Accordingly, NCR is directly related to distance. Therefore, safe threshold distances have been calculated based on other parameters. For example, the longitudinal dimension (L_D) of the proposed domain is presented in Eq. (2):

$$L_D = L * V^{1.26} + 30 * V + U \tag{2}$$

where L is the own ship length, V and U are ship speed and error in estimating ship length, respectively. Smierzchalski (2005) has proposed a definition of risk degree as a mathematical function of TCPA and DCPA, as shown in Eq. (3):

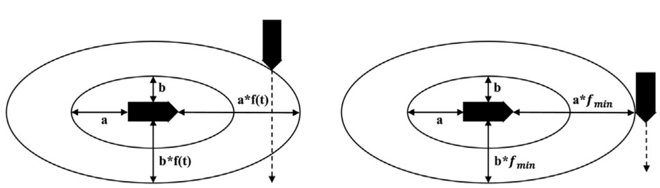
$$\min R = \begin{cases} a\left[e^{\left(\frac{DCPA}{D_b}\right)^{2b}} - 0.1\right]\left[\frac{T_b}{TCPA + c} - d\right], & DCPA < D_b,\quad TCPA < nT_b \\ 0 & ,\ DCPA > D_b, \\ TCPA > nT_b \end{cases} \tag{3}$$

where D_b and T_b are the safe distance and time to safe distance defined by the proposed hexagon-shaped area, a, b, c, d are the regulated parameters. As can be seen in Equation (2), this hexagon-shaped area is based on speed, allowing to set critical limits (D_b and T_b) dynamically.

However, employing the parameters of TCPA and DCPA has been considered useless by Szlapczynski (2006). Thereafter, the temporary approach factor (f_{min})—that is, the ratio of the distance between the two encountering ships to minimum acceptable distance—was proposed for integrating various ship domain models when appropriate. This factor was proposed due to the misleading/obscure aspect of DCPA in ship domain violation, as discussed in section 3.2. This study proposed a modified NCR model of Lisowski (2004), as shown in Eq. (4):

$$r = [a_1 f_{min}^2 + a_2 (\frac{T_{f_{min}}}{T_s})^2 + a_3 f(t)]^{-\frac{1}{2}} \tag{4}$$

While a_1, $a_2$and a_3 are coefficients dependent on the state of visibility, ship length and a kind of water area, $T_{f_{min}}$and T_s are the time to reaching the temporary approach ($f_{\min}$) value, and the time necessary to plan and perform a collision avoidance manoeuvre, respectively. $f(t)$ is the instantaneous scale factor of ship domain, and f_{min} the minimum value of $f(t)$, which utilizes the minimum distance between two ships on any given course. In fact, the difference between these two parameters is the position of the target ship. This approach substitutes DCPA and TCPA with f_{min} and $f(t)$, which take into account the ship itself rather than the safe distance from the ship. Fig. 5 illustrates the graphical representation of $f(t)$ and f_{min}. Furthermore, Szlapczynski and Szlapczynska (2016) have further extend the former study (Szlapczynski, 2006) by introducing two new parameter called degree of domain violation and time to domain violation.



(a) (b)

Fig. 5. Temporary approach factor ($f_{\min}$) and approach factor $f(t)$ (Szlapczynski, 2006).

Liu and Liu (2006) have defined collision risk as a function of DCPA and TCPA, as shown in Eq. (5).

$$Risk(t) = \begin{cases} 0 & ,\ DCPA_t \geq \lambda_{DCPA} \\ \frac{1 - e^{2(DCPA_t - \lambda_{DCPA})^2}}{2} + \frac{e^{2TCPA_t^2}}{2} & ,\ DCPA_t < \lambda_{DCPA} \end{cases} \tag{5}$$

Here, the parameter λ_{DCPA} was introduced, determined by restricted visibility and the condition of sight. The proposed risk definition was employed to evaluate the trainees' manoeuvrings in collision avoidance situations. The study has introduced a feasible methodology, allowing to learn cases by recording important data.

Balmat et al. (2009) introduced the maritime risk assessment (MARISA) model with the adoption of a fuzzy approach. This model combined static and dynamic risk factors: year of construction, flag state, gross tonnage, the number of companies, duration and type of detentions were determined as static factors, while sea state, wind speed, visibility, and night or day time were determined as dynamic factors. With this study, Balmat et al. (2009) modified the work of Degré (2003) with the contribution of weather conditions pointing to the dynamic nature of ship navigation.

In 2011, Balmat et al. (2011) revised the MARISA model by including speed (fuzzy) and shipping evaluation (non-fuzzy). While the MARISA model does not exactly portray the NCR and focuses on oil pollution prevention at sea, the modified version illustrates the individual risk of vessels for all situations, including collision. The risk assessment architecture of the study is presented in Fig. 6.

Speed evolution in this study considers zigzags or successive acceleration/decelerations as suspect manoeuvrings. These suspect manoeuvrings are detected by calculating the orthorhombic distance with the last and instantaneous geographic positions.

Wang (2010) introduced a new NCR model based on the dynamic calculation of the ship domain. This study determines the size of the ship domain by means of four radii (fore, aft, starboard, and port), which can be elliptical or convex. The determined ship domain is then transformed into a fuzzy environment to assess the individual NCR with the help of Eq. (6).

$$r = exp^{\left(-\left(\left(\frac{2x}{(1+sgnx)\sigma_{fore}+(1-signx)\sigma_{aft}}\right)^k + \left(\frac{2y}{(1+sgny)\sigma_{star}+(1-signy)\sigma_{port}}\right)^k\right)\right)} \tag{6}$$

where σ_{fore}, σ_{aft}, σ_{star}, σ_{port} are related to the proposed ship domain radius, x and y are longitudinal and lateral distances between the ships, respectively. The power k determines the shape of the ship domain. $sgnx$ and $sgny$ are either negative or positive, depending on the sign of the distances. This equation proposes the spatial collision risk of the navigating ship whose ship domain changes dynamically. Comparison of the proposed model with existing ship domain models in simulation presents more coherent (in reaction time) collision risk awareness for each encounter situation. Modifying existing ship domain models is a distinguished perspective, although it can lead to heavy dependency on preferred ship domain model. Thanks to this insight, the proposed model enables overcoming the limitation of traffic geometry.

In addition to commonly known parameters, such as DCPA and TCPA, several authors have introduced navigation-specific variables in order to take NCR assessment further. For instance, Bukhari et al. (2013) proposed the parameter of the variance of compass degree (VCD), which is the difference between two consecutive bearings. In this study, the parameters VCD, DCPA and TCPA were used to construct an NCR assessment model. These parameters were transformed into fuzzy membership functions, illustrated in Fig. 7, and the NCR assessment model was structured as a fuzzy rule-based model. In fact, VCD is the difference between two consecutive bearings, representing the

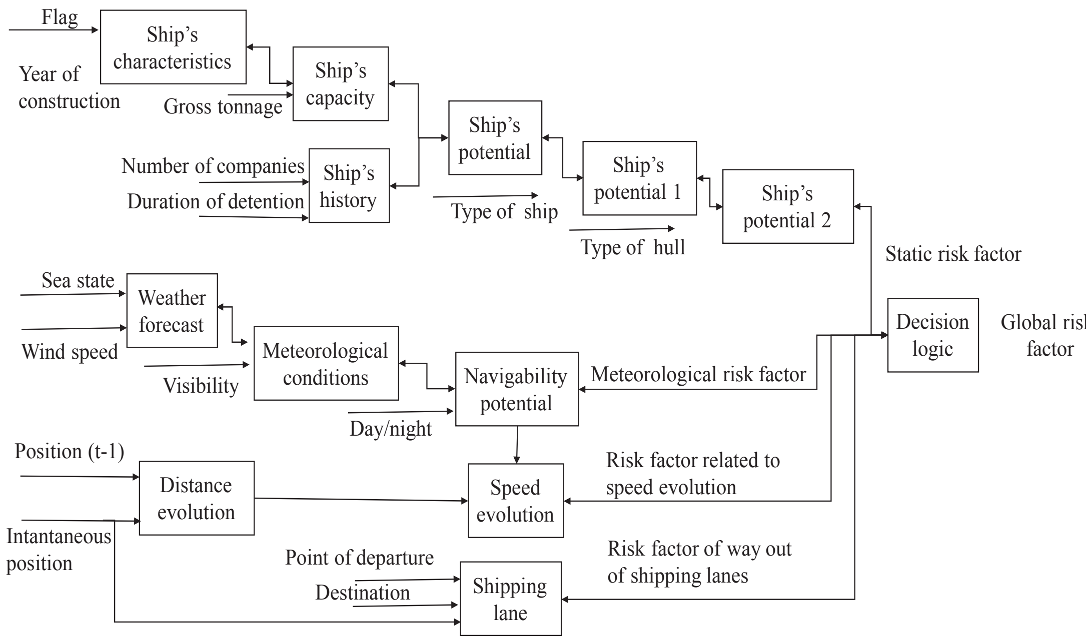


Fig. 6. Risk assessment architecture of Balmat et al. (2011).

degree of the change of the bearing. The aim of this study was to construct an automatic collision risk assessment interface, lightning the workload of VTS officers.

Smolarek and Śniegocki (2013) accepted wind speed as an important determinant for safe manoeuvring in restricted waters. The authors analysed the risk by taking into consideration the parameters of ship speed, wind speed and wind direction with a generalized linear model. The fitted model was validated by a chi square approach. The proposed NCR model assumes a higher risk degree when the ship position is far from the centreline. Although the relation between the parameters and the risk degree has not been examined, it can be pointed out that the speed parameter clearly has the highest linear relationship with the risk degree.

In addition to the above-mentioned models, nonlinear support vector machines (SVM) were employed by Gang et al. (2016) in order to estimate the collision risk index. The collision risk estimation model proposed in this study is similar to that of Ahn et al. (2012). However, Gang et al. used fuzzy comprehensive evaluation theory without expert knowledge, instead of the fuzzy inference rules acquired from the knowledge of watching officers. The membership function formulations of the parameters of DCPA, TCPA, distance, relative bearing and velocity ratio are presented in Eqs. (7)–(11), respectively. These membership functions are similar to those presented in Chen et al. (2015).

$$u_{DCPA} = \begin{cases} 1 & , |DCPA| < 1 \\ \left(\frac{d_2 - |DCPA|}{d_2 - d_1}\right)^2 & , d_1 \leq |DCPA| \leq d_2 \\ 0 & , |DCPA| > d_2 \end{cases} \tag{7}$$

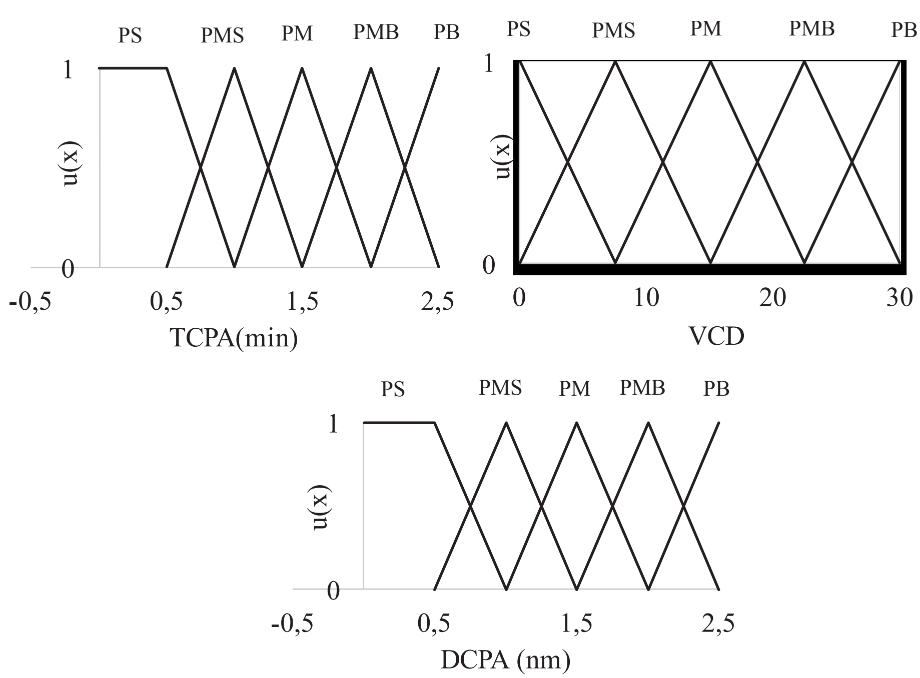


Fig. 7. Proposed membership functions of parameters (Bukhari et al., 2013).

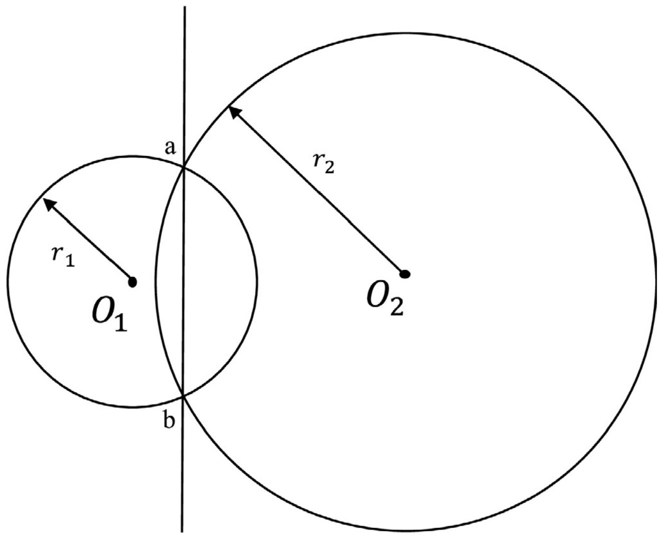


Fig. 8. The radical axis of two guarding rings (Kao et al., 2007).

$$u_{TCPA} = \begin{cases} 1 & , |TCPA| < 1 \\ (\frac{(t_2 - |TCPA|)}{t_2 - t_1})^2 & , t_1 \le |TCPA| \le t_2 \\ 0 & , |TCPA| > t_2 \end{cases} \tag{8}$$

$$u_{D_R} = \begin{cases} 1 & , 0 < D_R < 1 \\ (\frac{D_2 - D_R}{D_2 - D_1})^2 & , D_1 \le D_R \le D_2 \\ 0 & , D_R > D_2 \end{cases} \tag{9}$$

$$u_{\theta_T} = \frac{1}{2}[cos(\theta_T - 19) + \sqrt{\frac{440}{289} + cos^2(\theta_T - 19)}] - \frac{5}{17} \tag{10}$$

$$u_K = \frac{1}{1 + \frac{2}{K\sqrt{K^2 + 1 + 2Ksin(C)}}} \tag{11}$$

where d_1 and d_2 are the minimal safe encounter distance and absolute safe encounter distance, $t_1$and t_2 are defined as a function of speed, and $d_1$and d_2. θ_T are the relative position of the target ship from the own ship. K is the velocity ratio of the two vessels. Here, NCR is defined as the weighted product of these membership functions. The output of the fuzzy comprehensive evaluation is employed as the collision risk label of a support vector machine model, utilizing own ship speed, target ship speed, own ship position, target ship position, the distance between the two ships, and relative bearing. However, details about the data selection and the determination of collision risk (for training and testing data) are equivocal, and the authors recommend actual vessel data for applicability.

In addition to the proposed limits of Hilgert and Baldauf (1997)—such as hydrodynamic safe passing distance (C_H), safe passing distance (C_A) and safe range (R_A)—Wen et al. (2016) evaluated the Safe Passing Distance (SPD) as "safe distance of approach" (SDA) regarding COLREG Rule 8 and proposed limit values for ship to ship encounters. The authors defined NCR as the multiplication of DCPA- and TCPA-based fuzzy functions, as shown in Eq. (12) and (13):

$$u_{DCPA} = \begin{cases} 1 & , |DCPA| < d_1 \\ (\frac{(d_2 - |DCPA|)}{d_2 - d_1})^{3.03} & , d_1 \le |DCPA| \le d_2 \\ 0 & , |DCPA| > d_2 \end{cases} \tag{12}$$

$$u_{TCPA} = \begin{cases} 1 & , |TCPA| < t_1 \\ (\frac{(t_2 - |TCPA|)}{t_2 - t_1})^{3.03} & , t_1 \le |TCPA| \le t_2 \\ 0 & , |TCPA| > t_2 \end{cases} \tag{13}$$

where $d_1$and d_2 constitute parameters concerning SDA and are determined by the relative bearing of the target ship, $t_1$and t_2 are time parameters indicating the time remaining to the last collision avoidance manoeuvring. In fact, the authors assume the existence of a collision risk when the distance of two ships is 8 nautical miles. Yet, they also consider 12 ship lengths as the distance of last-minute avoidance.

3.2. Moderate realist models

Moderate realist models are quite similar to the strong realist approach, with only a few dissimilarities. The characteristics of moderate realist models were defined by Goerlandt and Montewka (2015) as follows:

i. It heavily relies on data collected from the system or on engineering/natural science models.
ii. Expert judgment is considered a source of evidence, but knowledge generated by experts is seen as a last resort and/or is seen as truth-approaching.
iii. Evidence uncertainty is not considered, or only sporadically mentioned.

At harbour entrances, VTS systems can be overloaded when assessing the danger of navigation, if the waterway is too congested. Therefore, Kao et al. (2007) proposed a fuzzy logic method to alleviate this problem. Three fuzzy membership functions (speed, length of ship, and sea state) were proposed to determine the radius of a guarding ring. The fuzzy guarding ring was derived from the concept of the ship domain and based on the idea that the vessel's collision risk increases when the ship domains become closer, as shown in Fig. 8.

The length of the radical axis, ab, of the two circles O_1 and O_2 (considered the ship domains) increases whenever two ships are approaching, according to the Pythagorean theorem. However, the interaction between the two guarding rings was evaluated with the help of the membership functions of the proposed parameters, instead of any mathematical calculation. A total of 27 fuzzy rules were proposed for the degree of the guarding ring, without any expert judgement. Furthermore, the study proposed a calculation of the degree of collision risk (u_{danger}), as can be seen in Equation (14).

$$u_{danger} = \begin{cases} 1 & , \Delta t = 0 \\ 1 - 2(\frac{\Delta t}{\tau})^2 & , 0 \le \Delta t \le \frac{\tau}{2} \\ 2(\frac{\Delta t - \tau}{\tau})^2 & , \frac{\tau}{2} \le \Delta t \le \tau \\ 0 & , \Delta t \ge \tau \end{cases} \tag{14}$$

The parameter τ is the safety time interval obtained by the membership function of speed, and Δt is the discrepancy of two collision points. While the definitions of τ and Δt were not clear, it was assumed that τ is the time to make the minimum safe distance, described as 0.9 nautical miles according to Goodwin (1975). The authors recommended this model as a tool for monitoring all ships in a congested harbour entrance. However, the author did not take into consideration the effect of multi-ship encounters.

Another important example of a moderate realist model was proposed by Mou et al. (2010). This model made use of the Safety Assessment Model for Shipping and Offshore on the North Sea (SAMSON)'s accident number estimation model to define collision risk in busy waters. The authors added the TCPA, CPA and encounter angle parameters as multipliers to SAMSON's model. The equation of the proposed collision risk model is as follows:

$$R_{Colli} = R_{basic} * R_{tcpa} * R_{cpa} * R_{angle} \tag{15}$$

In the equation, R_{basic} stands for basic risk (static risk factors: ship type, size, and so on), and R_{tcpa} and R_{cpa} represent the exponential function of TCPA and CPA, respectively. R_{tcpa} and R_{cpa} are determined based on expert opinion. R_{angle} is a predetermined factor based on the

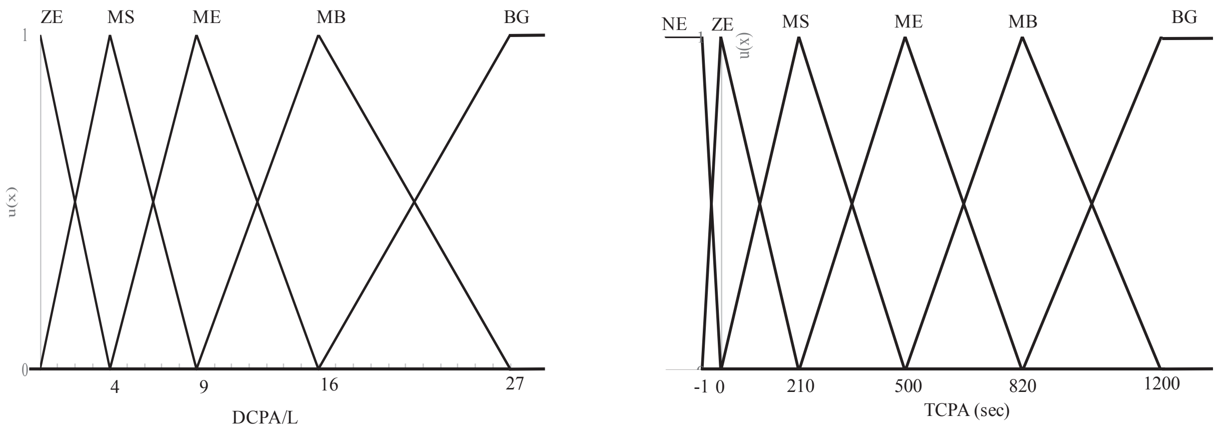


Fig. 9. Modified membership functions of DCPA and TCPA (Ahn et al., 2012).

course difference between the own and the target ship. The unique characteristic of this model is the estimation of CPA by using course difference, length of ship, speed and relative difference separately, with linear regression and AIS database. This model, which includes a maritime accident data set, was proposed as a helpful tool for monitoring risk due to severity of maritime traffic.

Since questionnaires incorporating perceived risk level can be quite subjective, Ahn et al. (2012) proposed an interviewee-independent method, which can be deemed a pioneering work. This is achieved with the help of the rule-based collision risk table modified from the study by Hara and Hammer (1993), as well as the fuzzy membership functions of DCPA (Koyama and Yan, 1987) and TCPA. Hara and Hammer (1993) acquired the knowledge of watching officers from experimental results using a ship handling simulator. Because the number of rules obtained from Hara and Hammer (1993) was insufficient to represent the degree of the collision risk, the study by Ahn at al. (2012) employed an adaptive network-based fuzzy inference system to increase the number of membership functions of DCPA and TCPA. The modified membership functions of DCPA and TCPA and the modified fuzzy inference table are presented in Fig. 9 and Table 4, respectively.

The output of the fuzzy inference system was employed as the collision risk label of a neural network model, utilizing the own ship's speed, target ship speed, the own ship's heading, target ship heading, the distance between the two ships, and ship domain (Zhao et al., 1996) as input vector. Restricted visibility (Cockcroft et al., 2012), topographical characteristics (Lee and Rhee, 2001), and high speed constraints were also adopted in this NCR evaluation in order to approximate a complex maritime environment. Simulation results show that a neural network-based model is more realistic than the fuzzy inference system. Ahn et al. (2012) also designated different ship domains for restricted and open sea areas, having particular idiosyncrasies. The NCR assessment methodology of this study is quite feasible for the maritime environment. While the severity of navigation can be evaluated on the basis of navigation-specific parameters such as DCPA, TCPA and VCD, the actual parameters affecting the severity of navigation are system parameters such as speed, heading and distance.

Table 4
Modified fuzzy inference table.

DCPA/L	TCPA					
	NE	ZE	MS	ME	MB	BG
ZE	−1.0	0.998	0.790	0.605	0.399	0.206
MS	−1.0	0.804	0.670	0.485	0.313	0.202
ME	−1.0	0.582	0.453	0.291	0.200	0.109
MB	−1.0	0.447	0.337	0.233	0.139	0.082
BG	−1.0	0.195	0.187	0.108	0.064	0.017

Zhang et al. (2016) pushed their previous study (Zhang et al., 2015) forward by including in the model a new parameter called minimum distance to collision (Montewka et al., 2010). Vessel size was also employed in the model, together with a ship domain concept, instead of the distance between the two ships, as shown in Eq. (16).

$$VCRO(x, y, z, l_\alpha, c_{MDTC}) = (k * (x - l_\alpha)^{-1} * y) * c_{MDTC} \quad (16)$$

In this equation c_{MDTC} is the minimum distance to collision derived from another study (Montewka et al., 2010). l_α is the distance between the own ship and the ship domain in the line of the other ship. Conducted scenarios shown that the model is not valid near harbours because of the close distances. In fact, the study did not define the risk degree in encounters of less than one nautical mile. The authors also stated that the VCRO values of scenarios were in line with the expert judgments utilized as a source of evidence.

Zhao et al. (2016) proposed an NCR assessment approach based on evidential reasoning for autonomous navigation in unmanned surface vessels. The authors pointed out that NCR assessment is the foundation for autonomous navigation and has three significant characteristics: ambiguity, uncertainty, and instantaneity. The DCPA, TCPA, the distance between the two vessels, relative bearing and relative velocity based fuzzy membership functions—derived from other studies (Li and Pang, 2013; Zhou and Wu, 2004)—were employed to assess the NCR. Zhao et al. defined the NCR as a weighted multiplication of fuzzy membership functions utilized in the calculation of the belief degrees for evidential reasoning, as shown in Eq. (17).

$$NCR = \left(\sum_{n=1}^{N} (\lambda | l_n) * \alpha(l_n) + \left(\frac{\lambda_{U,n}}{N}\right) * \sum_{n=1}^{N} \alpha(l_n)\right) * 0.25 + 0.5 \quad (17)$$

$\alpha(l_n)$ is the risk representation value of grade l_n with belief degree, $(\lambda|l_n)$ is the confidence degree of risk grade and $\lambda_{U,n}$ is the representation of the overall uncertainty that brings together all factors. Basically, belief degree is formulated as in Eq. (18).

$$\alpha_{n,i} = \frac{\gamma_i - \beta_{down}}{\beta_{up} - \beta_{down}} \quad (18)$$

γ_i is the value of the membership function between 0 and 1. β_{down} and β_{up} are the risk interval into which γ_i falls. Here, the NCR assessment is not basically the weighted multiplication of membership functions as in other studies (Chen et al., 2015, 2014; Xu et al., 2010), but a combination of belief degrees. Furthermore, this study calculates the NCR in order to activate the prompt alert of collision avoidance for an unmanned surface vehicle.

Because the previous model (Zhang et al., 2016) employed a static ship domain and was not capable of giving any information about the dynamic state of the ship, Zhang et al. (2017) applied a different domain model (Kijima and Furukawa, 2003) to display the dynamic NCR

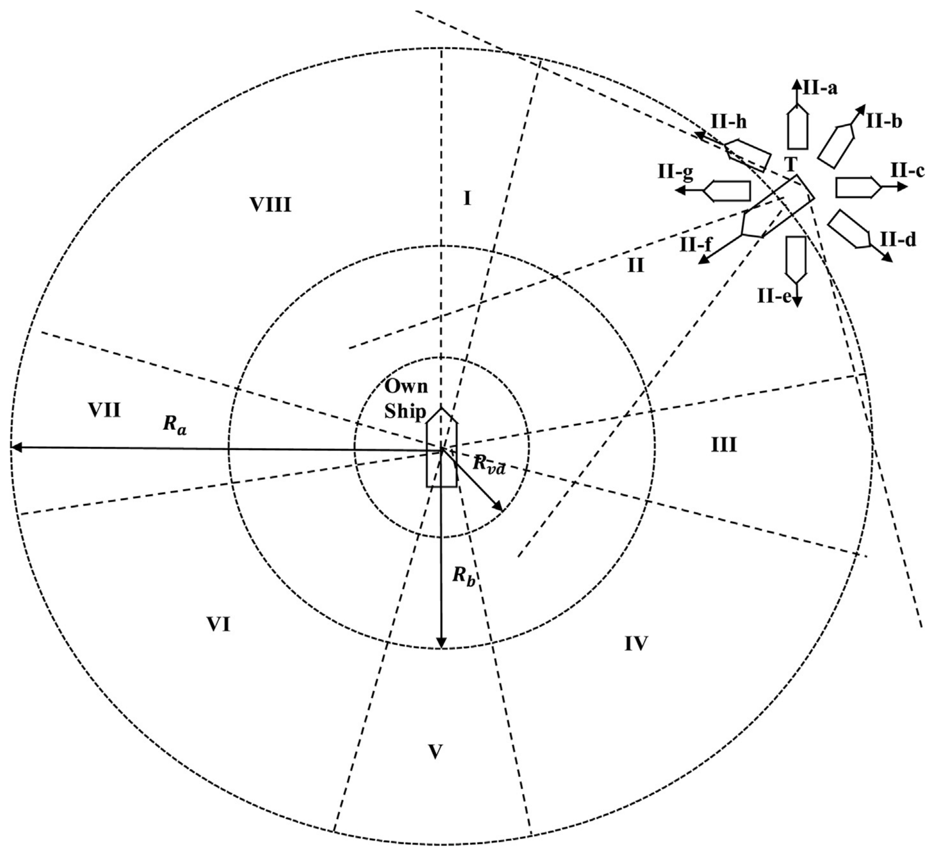


Fig. 10. Relative collision situation in ocean navigation.

of ship navigation. The proposed model combines the merged VCRO (average VCRO rank of two encountered ships), the VCRO change rate and the ship pair size, and classified them with the help of fuzzy clusters. Fuzzy rules were established with the fuzzy k-means method, together with expert knowledge, to assess NCR. Utilizing the ship domain model of Kijima and Furukawa (2003) enabled the integration of ship manoeuvring characteristics into the system, distinguishing the new VCRO model from prior studies. The ship manoeuvring characteristics of the model include the time to a 90-degree heading and the tactical diameter, indicating the response time and pattern of a ship when changing direction in case of emergency. Another advantage of this over prior VCRO models is its dynamic state, enabling one to monitor dynamic changes in ship to ship encounters.

3.3. Moderate constructivist models

Unlike strong and moderate realist models, moderate constructive models assume risk to be the mental construct of an expert. While the data come from the system, the risk degree is extracted from the expert's knowledge according to the system data. The main characteristics of the moderate constructivist model are described by Goerlandt and Montewka (2015) as follows:

i. The analysis is presented as the reflection of an assessor's mental construct.
ii. It relies on data collected from the system, engineering/natural science models, as well as expert judgment.
iii. Evidence uncertainty is not considered.
iv. Stakeholders are not involved in analysis process.
v. Non-epistemic values are excluded from the risk characterization.
vi. Contextual risk attributes are not considered.
vii. There exists a clear link to decision-making, in terms of a managerial review, where other decision criteria are considered along with the risk analysis.

The study by Inoue (2000) constitutes one example of a moderate constructivist model. The author proposed an environmental stress model based on linear regression, employing the time to collision (TTC) parameter to estimate ship handling difficulty in restricted and congested waterways. The TTC parameter can be assumed to consist of the time needed to reach any obstacle or ship. The proposed model is written as follows:

$$SJ_L^{(i)},\ SJ_S^{(i)} = \alpha + \beta * TTC \tag{19}$$

The linear relationship between TTC and stress level of officer on watch (OOW) is introduced by the α and β coefficients. $SJ_L^{(i)}$ and $SJ_S^{(i)}$ are perceived stress values according to the regression model on the relative bearing of i.th degree of the own ship from land objects and other ships, respectively. This environmental stress model was used for the comparison of two navigational aids (ARPA and recommended Collision Danger Presentation) by Pedersen et al. (2003).

Subsequently, Chin and Debnath (2009) utilized ordered probit regression model to formulate collision risk in port waters. The model was fitted with survey results of the perceived collision risk from 160 pilots, based on the TCPA and DCPA variables for night/day condition and four different vessel classes. The regression model of the study is presented as follows:

$$T_m = \beta_1 * DCPA + \beta_2 * TCPA \tag{20}$$

While T_m indicates ordered risk level, $\beta_1$and β_2 are regression coefficients. The results obtained from the study show that DCPA is more prone to affect perceived collision risk than is TCPA. This NCR model was utilized in the Navigational Traffic Conflict Technique (Debnath and Chin, 2010) to overcome the limitation of the number of collision records in any given waterway, such as port anchorages (Debnath and Chin, 2016). The Navigational Traffic Conflict Technique based on the

NCR model presents a practical way to overcome the limitations of the dependent variables of NCR assessments in port waters. The same methodology may be applicable and useful for other spaces of maritime transportation.

However, Perera et al. (2011) introduced a fuzzy rule based decision-making system to improve the safety of oceangoing vessels. The NCR degree is based on distance, relative bearing of the target vessel, encounter angle and relative speed. Fig. 10 offers a graphical representation of encounter situations.

Own ship and target ship (T) collision regions are divided into eight regions in accordance which collision avoidance decisions, and an NCR is formulated. The boundary and limits of the regions (I, II, II, IV, and so on), distances (R_{vd}, R_a, etc.) and other parameters are defined as a fuzzy membership functions. Although the study has focused on extracting all encounter situation for collision avoidance, the COLREG rules and regulations have been considered for the critical collision condition situation in near proximity. The authors applied expert knowledge in order to fill this gap. However, the steps behind the expert knowledge extraction have not been presented. Even so, their NCR assessment approach can provide evidence for near proximity encounters where regulation improvements can be made within COLREG.

However, several studies (Goerlandt et al., 2015; Zhang et al., 2015) criticized the parameters DCPA and TCPA, as they lead to obscure risk interpretation. This criticism is premised on the idea that a low CPA value does not signify a risky encounter if the bow-cross range (the distance at which the second vessel passes ahead of the bow of the first vessel) is wide. In other words, port to port or starboard to starboard encounter types can be safe, even though the CPA value is low. To overcome this deficiency, Zhang et al. (2015) proposed a vessel conflict ranking operator (VCRO) to evaluate the severity of two ship encounters. The mathematical function of the model was built based on the distance between the two ships (x), the relative speed (y), and the difference between their headings (z) as follows:

$$VCRO(x, y, z) = ((kx^{-1}y)(m * \sin(z) + n * \sin(2z)) \quad (21)$$

k, m, n represents the coefficients estimated by the least square method, and these coefficients have been determined based on expert judgement. Harbour approaches were excluded from the application of the model. This exclusion emphasizes the idiosyncrasies of different waterways. The focus of the study was to extract the near miss collision data to evaluate the maritime transportation safety, rather than to assess NCR.

In addition to employing TCPA and DCPA, which do not fully state the ship encounters' level of severity, Lopez-Santander and Lawry, 2017 also adopted relative situation (head-on, crossing, overtaking), color (red, green) and trajectory variability (erratic, not erratic) as NCR estimation parameters. The results of this ordered probit model revealed that DCPA has the most significant effect on the perceived risk, with the highest absolute coefficient value (0,395). By contrast, the estimate of the TCPA coefficient constitutes the lowest value (0,0249), which is a surprising result for the maritime environment. The performance of the model was evaluated based on the data set of the original questionnaire's responses. Assuming that collision avoidance is the ultimate objective of assessing risk, the study was proposed a pathfinding algorithm employing the risk distribution of any given vessel.

Since it is not feasible to examine all NCR studies in equal detail, we introduce information on other NCR assessment studies (Chen et al., 2014; Perera and Guedes Soares, 2015; Ren et al., 2011, etc) in Tables 3 and 5.

4. Application of NCR assessments with collision avoidance

This section reviews navigational collision avoidance studies that have adopted NCR assessment procedures. In these studies, NCR assessment processes have been presented as a complementary part of navigational collision avoidance systems. However, collision avoidance can be also achieved with the help of any established method (Lopez-Santander and Lawry, 2017), other than NCR assessment.

Table 5
Occurrence of NCR parameters.

Key	Parameter	Number of Occurrences	Rate of Occurrence
M1	TCPA	19	54,3%
M2	DCPA	18	51,4%
M3	Relative bearing	13	37,1%
M4	Distance	12	34,3%
M5	Speed	7	22,1%
M6	Length	5	15,2%
M7	Relative speed	4	11,4%
M8	Visibility	4	11,4%
M9	Breadth	3	8,6%
M10	Day/Night	3	8,6%
M11	Sea State	3	8,6%
M12	Wind Speed	3	8,6%
M13	Advance	1	3,0%
M14	Encounter type	2	5,7%
M15	Flag	2	5,7%
M16	Heading	2	5,7%
M17	Kind of water region	2	5,7%
M18	Number of companies	2	5,7%
M19	Number of detentions	2	5,7%
M20	Ship domain	2	5,7%
M21	Tactical diameter	1	3,0%
M22	Tonnage	2	5,7%
M23	Velocity ratio	2	5,7%
M24	Years of construction	2	5,7%
M25	Relative distance	1	2,9%
M26	Approach factor	1	2,9%
M27	Bow cross range	1	2,9%
M28	Color	1	2,9%
M29	Encounter angle	1	2,9%
M30	Minimum distance to collision	1	2,9%
M31	Geographic position	1	2,9%
M32	Rate of change of relative direction	1	2,9%
M33	Shipping evaluation	1	2,9%
M34	Speed change	1	2,9%
M35	Temporary approach factor	1	2,9%
M36	Trajectory variability	1	2,9%
M37	TTC	1	2,9%
M38	VCD	1	2,9%
M39	VCRO	1	2,9%
M40	VCRO Change rate	1	2,9%
M41	Wind direction	1	2,9%

The studies discussing collision avoidance systems with NCR assessment include those presented here: A pioneering work Szlapczynski (2006) proposed a numerical algorithm, mainly based on finding a safe value (f_{min}) for any course in the case of domain violation ($f_{min} > 1$) provoking the ship domain's rotation. Rotating the ship domain leads to a new ship domain. This new ship domain is determined by a new course in the case of domain violation. Also, Ahn et al. (2012) employed the NCR threshold value of 0.6 to provoke collision avoidance action, with speed and course alteration. In this study, an expert system tool was utilized to determine the proper order for safe manoeuvring, particularly for those complex encounter situations where the COLREG regulations are insufficient. Furthermore, Pietrzykowski et al. (2012) introduced an integrated navigational decision support system (NAVDEC) to meet the trend of converting navigational information systems into decision support systems. The collision risk estimation approach was implemented with the help of COLREG, the principles of good sea practice, and criteria used by marine officer experts in the NAVDEC. Thereafter, Tam and Bucknall (2013) employed proxy metric based collision risk values to determine the COLREG compliant collision avoidance manoeuvre, including a standard change in heading (30°). Another course alteration procedure was proposed by Wen et al. (2016) in case the NCR exceeds a level of 0.5. The proposed course alteration occurs in 0.1° increments. A further COLREG compliant real-time collision avoidance model was introduced by Zhao et al. (2016). The authors utilized a generalized ORCA algorithm for their real-time collision avoidance model. Since then, Lopez-Santander and Lawry (2017) introduced their NCR estimation model to avoid collision situations by adopting an optimization algorithm. Safe navigation routes can be obtained with the application of the risk cost function of the optimization algorithm in a multi-ship encounter environment.

The above-mentioned studies altogether demonstrate that the NCR assessment process facilitates not only a risk threshold value at which the avoidance manoeuvre is initiated, but also the timing of when to stop the precautions substantiating the NCR and the collision avoidance relationship. Moreover, NCR assessments were also adopted for trajectory planning (Śmierzchalski, 2005), maritime traffic monitoring (Mou et al., 2010), near miss risk (Zhang et al., 2017), VTS support (Bukhari et al., 2013), preventing oil pollution (Balmat et al., 2011), and performance evaluation (Pedersen et al., 2003).

5. Parameter analysis

This section will review the studies from the perspective of the parameters used in NCR assessment studies in a comprehensive manner. As a first finding of this section, the number and rate of occurrence of the parameters used in these studies are presented in Table 5.

Table 5 reveals that more than half of the NCR studies have adopted DCPA and TCPA in their risk assessment model. Also, relative bearing, distance, speed and length feature as the other most commonly used parameters. The distribution of the most commonly employed twenty parameters (M1 to M20) is introduced in Table 6. It is virtually impossible to capture any trend of the number of parameters increasing or decreasing by year. Additionally, most studies prefer to employ DCPA and TCPA, in spite of their proposed alternatives. The relative bearing parameter has not featured in studies after 2010. It is also noteworthy that there exists no significant discrimination between the parameters presented in Table 5 from the perspective of area-specific application for the open seas, or restricted waters, as seen in Table 6. The distribution of the other twenty parameters (M21 to M40) are presented in Appendix A.

As a matter of fact, mariners' judgment about collision risk is also heavily dependent on these parameters. Also, some of these parameters are clearly laid out in COLREG. For example, COLREG Rule 7 (b) recommends the use of radar equipment, which determines TCPA and DCPA as early warning of collision risk. Moreover, rule 7 (d) assumes collision risk in a steady relative bearing. However, environmental parameters (sea state, wind, water depth, day/night, visibility) have rarely been employed, although they are major factors affecting ship dynamics and mariners' judgment.

We have analysed the distribution of the ten most frequent parameters (M1-M10) in respect to the risk approaches. The results obtained are illustrated in Fig. 11 in order to clarify parameter preference.

As seen in Fig. 11, the parameters TCPA, DCPA, relative bearing, distance, speed and length are used in each risk approach, while the visibility and breadth parameters only occur in the strong realist approach. The day/night parameter is not employed in moderate realist risk approaches. The general tendency of risk approaches regarding the parameter selection may give insight for future research, not only to

Table 6
Distribution of parameters (M1-M20) in NCR studies.

Authors	RA	AA	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20
Lopez-Santander and Lawry (2017)	3	NM	a	a	a																	
Zhang et al. (2017)	2	O,R						a														
Gang et al. (2016)	1	NM	a	a	a	a																
Wen et al. (2016)	1	O	a	a												a						
Zhang et al. (2016)	2	O,R			a	a			a													
Zhao et al. (2016)	2	NM	a	a	a	a																
Chen et al. (2015)	1	O	a	a	a	a																
Goerlandt et al. (2015)	3	O	a	a	a	a																
Perera and Guedes Soares (2015)	1	O,R					a											a				
Zhang et al. (2015)	3	O,R			a	a			a													
Chen et al. (2014)	2	R	a	a	a	a																
Bukhari et al. (2013)	1	R	a	a																		
Li and Pang (2013)	1	R	a	a		a																
Smolarek and Śniegocki (2013)	1	R					a							a								
Ahn et al. (2012)	2	R			a	a	a											a				a
Balmat et al. (2011)	1	O								a		a	a	a			a			a	a	
Perera et al. (2011)	3	O			a	a			a													
Ren et al. (2011)	1	NM	a	a	a																	
Meng et al. (2009)	1	NM	a	a																		
Mou et al. (2010)	2	R	a	a	a																	
Tam and Bucknall (2013)	1	R					a									a						a
Wang (2010)	1	O,R					a	a							a							
Xu et al. (2010)	2	O	a	a	a	a																
Balmat et al. (2009)	1	O								a		a	a	a			a			a	a	
Chin and Debnath (2009)	3	R	a	a								a										
Kao et al. (2007)	2	R					a	a					a									
Liu and Liu (2006)	1	NM	a	a																		
Szlapczynski (2006)	1	NM						a		a	a								a			
Smierzchalski (2005)	1	R	a	a																		
Lisowski (2004)	1	NM	a	a				a		a	a								a			
Lee and Rhee (2001)	1	O,R	a	a			a	a														
Inoue (2000)	3	R																				
Hilgert and Baldauf (1997)	3	R	a			a																

[a] 1 = Strong realist model, 2 = Moderate realist model, 3 = Moderate constructivist model; O = Open sea, R = Restricted waters, NM = Not mentioned, RA = Risk approach, AA = Application area.

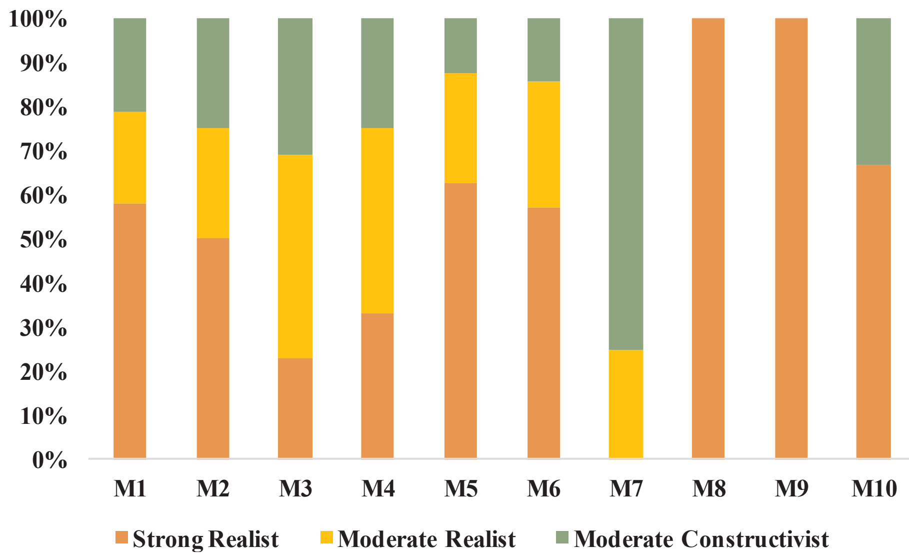


Fig. 11. Distribution of parameters by risk approach.

criticize—as in the studies of Goerlandt et al. (2015) and Zhang et al. (2015)—but also to support the parameters.

6. Discussion

In this section, we emphasize both current and complemental issues of NCR assessments in order to support the consistency of NCR assessments with the findings of our literature review.

Firstly, although the parameters clearly underlined by COLREG have been widely employed, hydro-meteorological data such as wind, current and wave height—which COLREG disregards—have rarely received attention in NCR assessment studies. Furthermore, the current speed affecting the ship movement, especially in narrow channels, did not directly figure in any of the NCR studies, as seen in Table 5. However, several authors (Kijima and Furukawa, 2003; Pietrzykowski et al., 2017) in their studies on collision avoidance manoeuvring stress the necessity of hydro-meteorological data. In fact, hydro-meteorological conditions affect the severity of encounter situations in the eye of the OOW. There may be three reasons behind the limited attention given to hydro-meteorological data. The first may be the shortcoming of the limit values or recommendations of the hydro-meteorological conditions for safe navigation in COLREG. The second may be the dominance of several navigation-specific parameters, such as TCPA and DCPA, not only in COLREG, but also in the maritime industry. Furthermore, DCPA and TCPA remain an industry standard in collision risk and collision avoidance systems (Chin and Debnath, 2009). The third may be the difficulty to calculate hydro-meteorological effects on the ship. Yet, there exist established standards for calculating wind, current and wave height force on the ship. For example, the recommendations set by the British Standard Institution and the OCIMF/SIGTTO (Oil Companies International Marine Forum/Society of International Gas Tanker and Terminal Operators Ltd, 1995) present applicable formulas for the calculation of hydro-meteorological effects. As example, the wind force calculation formulas on any given ship are presented in Eq. (22)-(24) (BSI, 2016):

$$F_{TW} = C_{TW}\rho_A A_L V_W^2 10^{-4} \tag{22}$$

$$F_{LW} = C_{LW}\rho_A A_L V_W^2 10^{-4} \tag{23}$$

$$F_{Wind} = F_{TW} + F_{LW} \tag{24}$$

F_{TW} and F_{LW} are transverse and longitudinal wind forces in kilonewton, respectively. ρ_A is density of the air in kg/m^3, A_L is the longitudinal projected area of the vessel above the waterline, and V_W is the design wind speed (m/sec). C_{TW} and C_{LW} are the transverse and longitudinal wind force coefficients for aft and bow, respectively. This calculation is more complex than the calculation of TCPA and DCPA. However, the inclusion of hydro-meteorological forces may increase the reliability of the NCR assessment in terms of the above-mentioned standards. Therefore, it seems to be of value to incorporate hydro-meteorological limit recommendations for each type of ship in COLREG.

Secondly, in the literature there are no specific standards for critical limits (safe distance, or time/distance of last-minute avoidance) for NCR. As mentioned above, different authors have attempted to define these limits within their formulations or assumptions based on their experience. However, critical limits (SPD, SDA, and time/distance of last-minute avoidance) can change based on environmental and dynamic factors, as well as the area navigated. Furthermore, limits can be interpreted differently by each mariner. For instance, while Wen et al. (2016) defined the distance of last-minute avoidance as 12 times the ship length, Xu et al. (2010) proposed it as the multiplication of visibility, water area status, human factor, and distance of last-minute action. Moreover, Tam and Bucknall (2013) and Xu et al. (2010) assumed an SPD of 0.25 and 1 nautical miles, respectively. Yet, Smierzchalski and Michalewicz (1998) stated that SPD depends on weather conditions, sailing area, and ship speed. Undoubtedly, the reason behind the attempts to come up with different critical limits can be found in the fact that there exist no established limit values for safe navigation to be incorporated in NCR assessment. Furthermore, reliance on good seamanship in the case of collision avoidance, which COLREG recommends in ample time, may foster this tendency until more concrete limits are established. However, in addition to critical limits, some distance limits/specifications can be incorporated in NCR assessment studies. For example, IMO regulations (IMO, 2002) limit the maximum admissible tactical diameter and advance of newly built ships to 5 and 4.5 ship length, respectively. Also, the stopping ability of the vessel in case of a full astern crash stop should generally not exceed 15 ship lengths according to IMO (IMO, 2002). Although these are not limits concerning safe distance, they can provide information about the manoeuvring capability of ships and may be incorporated in last-minute avoidance actions.

Thirdly, NCR studies are lacking in terms of reliable validation. Regardless of this deficiency, strong realist models not considering expert judgment prevail among the NCR assessment studies. Due to the fact that the severity judgment concerning NCR is more complex than in any other transportation mode, validation of the NCR assessment models is subjective rather than objective. Therefore, Goerlandt and

Kujala (2014) proposed a comparative approach to evaluate the reliability of any ship collision risk analysis. The proposed approach can reveal the consistency and accuracy of models, by re-running them with different inputs (data, method, frequency, and so on). Therefore, employing the comparative approach of Goerlandt and Kujala (2014) may improve the reliability of NCR assessment models.

The current literature on NCR assessment discusses only open and congested/restricted sea areas, as shown in Table 6. The studies on port approach manoeuvring has not been given adequate consideration in the literature. Port approach manoeuvrings include not only navigation in port areas, but also berthing at the pier until the ship stops. As ports constitute the gateways of the maritime transportation network, NCR assessments that consider port approach manoeuvring will offer a most valuable contribution to maritime transportation risk analysis.

7. Conclusion

This study has attempted to classify NCR assessment studies based on a systematic approach and to examine in detail several of these studies according to their unique characteristics. This approach has revealed not only the great variety of studies, but also the gaps to be filled by future research. Trends in parameter selection, from which future NCR studies can benefit, have also been evaluated. As a result, this literature review may support navigational decision support system proposal studies in maritime transportation with the aim of enhancement of autonomous ship concept, such that researchers may attach more importance to parameter selection in the context of COLREG and the model they employ.

As recommendation for future work, we suggest that considering wind, current and wave height effects on a ship's dynamic, as well as establishing concrete safety limits—in spite of COLREG's lack of emphasis on these factors—can promote the coherence of NCR assessment models. In addition, all studies examine the open sea and congested/restricted sea areas, as shown in Table 6. It is also found that, the lack of studies concerning port approach manoeuvring can be considered as an important gap in the literature. As ports constitute the gateways of the maritime transportation network, we also recommend that future studies address NCR assessments considering port approach manoeuvring. Furthermore, the validation of NCR assessment models should be conducted in a systematic way, as proposed by Goerlandt and Montewka (2015). This approach will improve NCR assessment studies in the domain of maritime transportation.

Appendix A. Employed parameters

Other parameters not mentioned in the study have been presented in Table A1.

Table A1
Distribution of other parameters (M21-M41) in NCR studies

Authors	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30	M31	M32	M33	M34	M35	M36	M37	M38	M39	M40	M41
Lopez-Santander and Lawry (2017)								*								*					
Zhang et al. (2017)																			*	*	
Gang et al. (2016)			*																		
Zhang et al. (2016)										*											
Chen et al. (2015)			*																		
Goerlandt et al. (2015)							*														
Perera and Soares, (2015)											*										
Bukhari et al. (2013)																		*			
Smolarek and Śniegocki (2013)																					*
Balmat et al. (2011)		*		*									*	*							
Perera et al. (2011)									*												
Wang (2010)	*																				
Xu et al. (2010)																					
Balmat et al. (2009)		*		*																	
Szlapczynski (2006)						*									*						
Inoue (2000)																	*				
Hara and Nakamura (1995)					*							*									

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